Study of non-equilibrium effects and thermal properties of heavy ion collisions using a covariant approach [1]

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February 9, 2008 **Abstract:**

Non-equilibrium effects are studied using a full Lorentz-invariant formalism. Our analysis shows that in reactions considered here, no global or local equilibrium is reached. The heavier masses are found to be equilibrated more than the lighter systems. The local temperature is extracted using hot Thomas Fermi formalism generalized for the case of two interpenetrating pieces of nuclear matter. The temperature is found to vary linearly with bombarding energy and impact parameter whereas it is nearly independent of the mass of the colliding nuclei. This indicates that the study of temperature with medium size nuclei is also reliable. The maximum temperatures obtained in our approach are in a nice agreement with earlier calculations of other approaches. A simple parametrization of maximal temperature as a function of the bombarding energy is also given.

[1]Supported by the GSI-Darmstadt and the BMFT under contract 06TÜ736.

Heavy ion reactions from few MeV/nucl. to few GeV/nucl. provide an unique opportunity to study the non-equilibrium dynamics of finite size systems and also the thermal properties of hot and dense nuclear matter formed during the reaction. Unfortunately, the hot and dense nuclear matter exits only for very short time. In addition, there is no direct way to measure it and thus various theoretical models are very helpful in the sense that one can simulate the reaction from the start up to the final stage where experimental measurements are done. The intermediate energy heavy ion reactions show a non-equilibrium situation in momentum space. Therefore, for a reasonable understanding of the heavy ion dynamics, one has to take care of these non-equilibrium effects.

There have been some attempts to extract the temperature reached during the heavy ion reactions. Hahn and Stöcker [1] extracted the temperature from measured pion yields and got reasonable temperature of the system at the time of maximum compression. Later on, there were some attempts to extract the thermal properties of heavy ion collisions using dynamical models like Quantum Molecular Dynamics [QMD] [2] and Relativistic Boltzmann-Uehling-Uhlenbeck [RBUU] [3], [4]. These models include the non-equilibrium features. In the study using RBUU, one assumes that the thermalization is directly connected with the nondiagonal elements of the stress tensor and the pressure P can be calculated as the trace of this tensor. Therefore, from a given form of the nuclear equation of state (EOS), one deduces the temperature as a function of energy, density and pressure. In this approximation, one can extract two components of the temperature which originate from the transverse and longitudinal components of the stress tensor [3], [4].

Very recently, Faessler and collaborators [5-10] developed a novel approach to extract the thermal properties of hot nuclear matter formed in heavy ion reactions. In this approach, one starts from a microscopic picture of two interpenetrating pieces of nuclear matter and deduces the thermal quantities from the density of the nuclear matter and kinetic energy

densities obtained during the collisions. The extraction of the temperature is based on a Generalized Hot Thomas Fermi Formalism [GHTFF] [11], [12]. In our approach, the extraction of thermal properties of hot nuclear matter formed in heavy ion collisions is done in two steps :(i) First one has to simulate the heavy ion reaction using a reliable dynamical model which incorporates the non-equilibrium features and can generate the motion of all particles in phase space during the whole reaction time. (ii) Second using this information in phase space, one can calculate the nuclear matter and kinetic energy densities at each point in coordinate space and time. These matter and kinetic energy densities are used to extract local temperature, entropy etc. [5].

In all our previous attempts to study the thermal properties of heavy ion reactions [5-10], we have simulated heavy ion collisions using Quantum Molecular Dynamics (QMD) in a non-covariant form [13]. While using a non-covariant formalism, one has to assume that the size of relativistic corrections is small and hence one can neglect these corrections appearing from a covariant treatment. To avoid such assumption, in this paper, we couple our recently reported full covariant QMD [i.e. Relativistic Quantum Molecular Dynamics RQMD] [14], [15] with the hot Thomas Fermi Formalism and study the thermal properties of heavy ion collisions. In the following, we will first give a brief introduction of the formalism used in RQMD and then present our results about non-equilibrium effects and temperatures reached in heavy ion collisions.

The covariant generalization of QMD model is done in the framework of the Constraint Hamiltonian Dynamics. This approach dubbed as RQMD describes the propagation of all kinds of baryons in a Lorentz-invariant fashion. In this approach, important quantum features like Fermi motion of nucleons, respect of the Pauli-principle etc. are also taken into account. Here each nucleon of the colliding nuclei are represented by Gaussian wave-packets. The center of each Gaussian is chosen at the start of the reaction by a procedure which is

based on the random choice of the positions of the nucleons in coordinate and momentum space. This is done with the help of a standard Monte-Carlo procedure. The nucleons are distributed in each of the two nuclei in a sphere of radius R = 1.14 $A^{1/3}$ which is consistent with the liquid drop model. If the centers of two Gaussians are closer than a distance D_{min} = 1.5 fm, the choice of these coordinates is rejected and other coordinates are chosen. The momenta of the nucleons are chosen randomly between zero and the local Fermi momentum.

In RQMD, the Hamiltonian for an N-particle system is expressed in terms of 8N variables (4N position $q_{i\mu}$ and 4N momentum coordinates p_i^μ). This means that each particle carries its own energy and time. Since the physical events are described as the world lines in a 6N dimensional phase-space, extra 2N-1 degrees of freedom have to be eliminated and a global evolution parameter τ has to be defined. This can be achieved with the help of 2N constraints. In our approach, first N constraints are chosen as Poincaré invariant on mass shell constraints which request that the particles move on energy shell between the collisions [14], [15], [16]:

$$\xi_i = p_i^\mu p_{i\mu} - m_i^2 - \tilde{V}_i = 0 \qquad ; \qquad i = 1, ..., N. \tag{1}$$

Here $\tilde{V}_i$ are the quasi-potentials. The next set of constraints are chosen as time constraints. These time constraints fix the relative times of all particles and are defined as:

$$\chi_i = \sum_{j(\neq i)} \frac{1}{q_{ij}^2/L_C} \exp(q_{ij}^2/L_C) \qquad i = 1, ..., N-1, \tag{2}$$

$$\chi_{2N} = \hat{P}^\mu Q_\mu - \tau = 0. \tag{3}$$

with $\hat{P}^\mu = P^\mu/\sqrt{P^2}$, $P^\mu = \sum_i p_i^\mu$, $Q^\mu = \frac{1}{N}\sum_i q_i^\mu$.

The Hamiltonian is a linear combination of the Poincaré invariant constraints:

$$H = \sum_{i=1}^{2N-1} \lambda_i \Psi_i, \tag{4}$$

with

$$\Psi_i = \begin{cases} \xi_i & ; \quad i \leq N \\ \chi_{i-N} & ; \quad N < i \leq 2N-1. \end{cases} \tag{5}$$

The unknown λ_i in eq.(4) are determine in each time step using the condition that all 2N constraints must be fulfilled during the whole reaction. After solving eq.(4), the final equations of motion reads as [14], [15], [16]

$$\frac{dq_i^\mu}{d\tau} = 2\lambda_i p_i^\mu - \sum_{j=1}^{N} \lambda_j \frac{\partial \tilde{V}_j}{\partial p_{i_\mu}}, \tag{6}$$

$$\frac{dp_i^\mu}{d\tau} = \sum_{j=1}^{N} \lambda_j \frac{\partial \tilde{V}_j}{\partial q_{i_\mu}}. \tag{7}$$

The propagation of baryons is combined with quantum effects like stochastic scattering and Pauli-blocking etc.. In RQMD, the collision part is treated in a covariant fashion. Therefore, all quantities which determine the collision are Lorentz invariant. For more details see refs. [14], [15].

Here we couple the covariant simulation of heavy ion collisions with the generalized hot Thomas Fermi formalism. In the present study, we do not generalize the GHTFF to a relativistic version and thus use the same GHTFF as reported in earlier papers [5-10]. The relativistic generalization would mean that we assume two ellipsoids in momentum space rather than two spheres as taken in GHTFF [5-10]. In GHTFF, the extraction of temperature is based on local density approximation. We define in each local volume element of nuclear matter in coordinate space and at each time a "temperature" by the diffuse edge of the deformed Fermi-distribution consisting of two colliding Fermi spheres which is typical for a non-equilibrium distribution in heavy ion collisions. For more details, we refer the reader to ref. [5].

We consider two possible quantities to study the degree of equilibrium reached in heavy

ion collisions. The first quantity is the anisotropy ratio $< R_a >$ which is defined as

$$< R_a >= \frac{\sqrt{< p_x^2 >} + \sqrt{< p_y^2 >}}{2\sqrt{< p_z^2 >}}. \tag{8}$$

This anisotropy ratio is an indicator of the global equilibrium of the system. The word "global" is due to fact that this quantity does not depend on the local position and thus represents the equilibrium of the whole system. The full global equilibrium would mean that the values of $< R_a >$ are close to one.

The second possible quantity is the relative momentum of two colliding Fermi spheres which indicates the deviation from a Fermi sphere and by that from the local equilibrium. The concept of local equilibrium is used by the hydrodynamical models to simulate the heavy ion reactions [17]. The local equilibrium is represented by the average relative momentum $< K_R >$ between two colliding Fermi spheres and is defined as :

$$< K_R >=< |\mathbf{P}_P(\mathbf{r},t) - \mathbf{P}_T(\mathbf{r},t)|/\hbar >, \tag{9}$$

where

$$\mathbf{P}_i(\mathbf{r},t) = \frac{\sum_{j=1}^{A_i} \mathbf{p}_j(t)\rho_j(\mathbf{r},t)}{\rho_i(\mathbf{r},t)}, \qquad i = 1,2. \tag{10}$$

Here $\mathbf{p}_j$ and ρ_j are the momentum and density experienced by the j-th particle and i stands for either target or projectile. The relative momentum $< K_R >$ depends strongly on the local position $\mathbf{r}$ and hence it is an indicator of the local equilibrium. In the following, the study of local equilibrium, density and temperature is carried out in a central sphere around the centre of mass of the two colliding nuclei with radius of 2 fm. The averaged values are shown. For a self-consistent analysis, we study the heavy ion collisions by varying following three different situations i.e.

(i) A wide range of bombarding energies. This will give us an unique possibility to study the different phenomena which govern the heavy ion dynamics at different energies. At low

energies the heavy ion dynamics is governed be the mean field whereas at higher energies, the frequent baryon-baryon collisions decide the fate of the collision dynamics of the heavy ion reactions.

(ii) Second, the variation of the impact parameter at a fixed bombarding energy. This gives us the possibility to study the effect of the position of the colliding nuclei at a fixed bombarding energy. In case of the central collisions, nuclear matter is highly compressed whereas in case of peripheral collisions, there is nearly no compression. Though, experimentally it is not possible to extract the impact parameter, there have been lot of attempts in recent years to find the approximate impact parameter for a specific collision.

(iii) The third one can study heavy ion reactions as a function of the mass of the colliding nuclei at a fixed bombarding energy and impact parameter. Heavy nuclei can be compressed far more than the light one. In order to have a fair study using different masses, we will often choose the impact parameter which is a certain fraction of the radii of the nuclei under consideration. Therefore, we define a scaled impact parameter in units of b_{max} which is equal to the radius of the target plus radius of the projectile. In these units the same impact parameter provides the possibility to study reactions of different nuclei with a corresponding geometry.

Fig.1 shows the time evolution of the anisotropic ratio $< R_a >$ for the reaction of ^{40}Ca -^{40} Ca at an impact parameter of 2 fm using the soft and the hard EOS's. We choose two typical bombarding energies i.e. 50 MeV/nucl. and 1 GeV/nucl.. One can also see two different phenomena which govern the process of thermalization at 50 MeV/nucl. and at 1 GeV/nucl.. Due to lack of free phase space at 50 MeV/nucl. about 80-85 % of the attempted collisions are blocked [15]. In other words, the mean field dominates the collision dynamics at 50 MeV/nucl. and hence one sees a smooth rise of the $< R_a >$ value from 0.5 to about 0.8 at 60 fm/c. When one sees the lower part of the figure where simulations at 1 GeV/nucl.

are shown, one recognizes that as soon as two nuclei touch each other, the $< R_a >$ ratio increases suddenly. Whereas when we take a Vlasov-mode (i.e. we suppressed all collisions by definition), we see that there is no sudden change in the $< R_a >$ value and the final value is about the same as at the start of the reaction. The evolution of the anisotropic ratio at 50 MeV/nucl. and 1 GeV/nucl. in the Vlasov-mode is quite similar : both show a smooth dependence. Therefore, this figure demonstrates the two different processes which are responsible for the thermalization at low and high energies. At low energies, the mean field is responsible for the equilibration whereas at higher energies the collisions are essential for the rise in the anisotropy ratio.

The dependence of the anisotropy ratio on the mass of the colliding nuclei is shown in the upper part of fig.2. The impact parameter is b = 0.25 b_{max}. It is interesting to note that the heavier nuclei are able to equilibrate more than the lighter nuclei. This can be understood on the ground that the number of collisions per nucleon for the ^{40}Ca -^{40}Ca reaction is larger than for the ^{12}C -^{12}C reaction. These collisions are responsible for thermalization. If one extrapolate this result to heavy systems, one can assume that for very heavy masses, one may be able to get nearly global equilibrium. Further, we also see that the thermalization process starts a bit later for heavier nuclei than for the lighter ones. From the above analysis, it is clear that for the reaction considered here, no global equilibrium is reached. The anisotropy ratio $< R_a >$ reached in all reactions considered here is less than one. It means that the average kinetic energy in the transverse direction is lower than that in the longitudinal direction.

We now study the local equilibrium. In the following we will concentrate on the bombarding energies up to 500 MeV/nucl. only.

The time evolution of the relative momentum $< K_R >$ is shown in lower part of fig. 2 using the hard EOS. Here five systems ^{40}Ca -^{40}Ca, ^{28}Si -^{28}Si, ^{20}Ne -^{20} Ne, ^{16}O -^{16}O, ^{12}C-^{12}C

are considered at an impact parameter b = 0.25 b_{max}. It is interesting to see that the relative momentum is very large at the start of the reaction and finally at the end of the reaction, the value of $< K_R >$ is nearly zero. This means that at the end of the reaction, the local equilibrium is nearly reached. This can also be due to fact that the matter density at this last phase of the reaction is very small (see e.g. fig.6). One also sees that at the start of the reaction, heavier masses show smaller values of $< K_R >$. This is due to fact that in a covariant approach, we have Lorentz-contracted initial distributions in coordinate space which increases the distance of surfaces of heavier nuclei more at the start of the reaction as compared to lighter nuclei. The time evolution of relative momentum at different energies and impact parameters is shown in fig.3. It is interesting to note that at the end of the reaction, the relative average momentum for higher energies is less than for lower energies. (At lower energies most of the two-body collisions are Pauli-blocked and equilibration is slower). The variation of the relative momentum with impact parameter is more interesting. The starting value of the $< K_R >$ is nearly the same for all impact parameters, but the time evolution of $< K_R >$ is quite different for central and peripheral collisions. From the above study, it is clear that for all energies and reactions considered here, the local equilibrium is reached only at the last phase of the reactions. This , however, questions the validity of the hydrodynamical models for studying the heavy ion reactions at intermediate energies. All these results are in nice agreement with earlier calculations with non-covariant QMD [5].

The evolution of the local temperature and matter density is shown in fig. 4 for the reaction of ^{40}Ca -^{40}Ca at an impact parameter of 2 fm. One should note that the local temperature depends on the matter and kinetic energy densities. We here display the results for temperature at the bombarding energies E_{lab} = 125 MeV/nucl., 250 MeV/nucl., 375 MeV nucl., and 500 MeV/nucl.. One can see the following interesting results:

i Compared to low energies, the temperature and density reaches the maximal value

earlier for higher bombarding energies. This is simply due to the fact that the velocities of particles at low energies is far less than that at higher energies. In order to have a fair measure, one can rescale the reaction time with the boost velocity β_{cm}. The product [β_{cm} t] is a kind of a reaction distance of the two colliding nuclei. We notice that the value of this product β_{cm} t when temperature and density reaches its maximum value is nearly the same for all energies.

ii The size of the hot and dense zone depends strongly on the energy considered. One sees that at low energies, the hot and dense zone exits for a longer time than at higher energies.

iii The maximal value of the temperature varies linearly with the bombarding energy (see, however, fig.8). Whereas the increase in matter density with bombarding energy is very small. This shows that the major factor which causes the temperature is the kinetic energy i.e. the bombarding energy.

The effect of variation in impact parameter on temperature and density is studied in fig. 5. Here we simulate the reaction ^{40}Ca -^{40}Ca at the bombarding energy 500 MeV/nucl. using the hard EOS. It is interesting to note that at a fixed bombarding energy, the temperature and density shows a linear correlation which indicates that the knowledge of either of them can give us a rough knowledge of the behaviour of other quantity. This linear behaviour is understandable. By fixing the bombarding energy, the kinetic energy is fixed and thus the variation in matter density shows a linear effect on the temperature. The central collisions show a very high value of the temperature and density whereas peripheral collisions yield smaller values. In the case of central collisions, we have a large fraction of nucleons which are participants whereas in the case of peripheral collisions, almost all nucleons are spectators. One also sees that the variation in the impact parameter alters not only the maximal value of the temperature and the density but, it also affects the size of the hot and dense zone. From

figs. 4 and 5, it is clear that for studying the temperature and density, the bombarding energy and the impact parameter play a central role. Therefore, in fig. 6, we fix the bombarding energy and the impact parameter, but vary the mass of the colliding nuclei. It is impressive to note that when one fixes the impact parameter and the bombarding energy, the maximal value of the temperature reached is about the same for all masses i.e. the maximal value of the temperature is nearly independent of the mass of colliding nuclei whereas the matter density depends strongly on the mass of the colliding pair. One can also see that the temperature and density reaches the maximal value for later times in heavier compared to the lighter systems. This different response of the temperature and the density to the total mass at a fixed bombarding energy and impact parameter indicates clearly that for determining the temperature, the major factor is the bombarding energy rather than the matter density. This result also shows that for studying the temperature and thermal properties, one can rely on medium size nuclei. This result is understandable since the bombarding energy fixes the possible excitation energy of the system.

The results presented in figs.4-6 are calculated with the hard EOS only. The influence of different equation of states on the temperature is studied in fig. 7. Here simulations of the reaction ^{40}Ca-^{40}Ca are shown at impact parameters b = 0 and 5 fm, respectively. The soft EOS creates far more temperatures than the hard EOS. We also note that when one goes to larger impact parameters, the difference in temperature using the hard and the soft EOS decreases. It is also worth to mention that all calculations presented in this paper are using the cross-sections parametrized by Cugnon [18]. If one does the calculations using in-medium cross-sections, one finds that the use of in-medium cross-sections results in significant enhancement in temperature [6]. Similar enhancement is found when one uses the cross-section derived from one-boson exchange model [19].

In fig.8, we plot the maximal value of the average temperature reached during the reaction

using a variety of colliding masses as a function of the bombarding energy. Here to constraint the colliding geometry, we fix the impact parameter (b = 0.25 b_{max}) to semi-central collisions. The maximum value of the temperature which is independent of the mass of the colliding nuclei can be parametrized in the following simple form:

$$T^{max} = 0.09466 \cdot E_{lab} + 4.934 \qquad \text{for} \;\; b = 0.25 b_{max}. \tag{11}$$

Our classical nature of the RQMD does not allow us to analyze the temperature for bombarding energies less than 40 MeV/nucl.. This parametrization of the maximum temperature can be used to extract the temperature for the bombarding energies between 40 MeV/nucl. and 500 MeV/nucl.. The linear dependence of the temperature on the bombarding energy is not surprising since the bombarding energy determines the possible maximum excitation energy. Further it is impressive to note the independence of temperatures on the masses.

These values of the maximum temperatures are in a nice agreement with the values obtained in ref. [1]. In these calculations, a thermodynamically consistent theory was applied to extract the temperature from measured pion yields.

In this paper we have coupled our recently developed microscopic approach for extracting the temperature with the full covariant RQMD. At low energies, the mean field keeps the nuclei together and hence they have time to develop to nearly full equilibrium. At higher energies, the frequent collisions are responsible for equilibrium and hence for thermalization. At higher energies no full equilibrium is reached. Further, heavier colliding nuclei show a better tendency for equilibrium. We have also studied the local equilibrium. We find that even at the last stage of the reaction, no full local equilibrium is reached. The local temperature depends strongly on the bombarding energy and the impact parameter whereas the maximal value of the temperature at a fixed bombarding energy and collision geometry (b/b_{max}) is nearly independent of the masses of the colliding nuclei. This behaviour is similar

to the resonance production or pion production which are also found to be nearly independent of the masses of the colliding nuclei. The maximum temperature which is independent of the masses of the colliding nuclei agrees with the one extracted from measured pion yields. Further a simple formula is also given to calculate the maximum value of the temperature.

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Figure Captions:

Fig.1 Time evolution of the anisotropy ratio $< R_a >$ as a function of the reaction time. The reaction under consideration is ^{40}Ca -^{40}Ca at an impact parameter b = 2 fm. The upper and lower parts of the figure represent results at bombarding energies 50 MeV/nucl. and 1 GeV/nucl.. The dotted line with open circles shows the results using the Vlasov-mode.

Fig.2 Time evolution of the anisotropy ratio $< R_a >$ as a function of the reaction time (upper part). Here we simulate five systems ^{40}Ca -^{40}Ca, ^{28}Si -^{28}Si, ^{20}Ne -^{20}Ne, ^{16}O -^{16}O and ^{12}C-^{12}C at the impact parameter b = 0.25 b_{max}. The lower part of the figure shows the averaged relative momentum $< K_R >$ as a function of the reaction time. The bombarding energy is 500 MeV/nucl..

Fig.3 Time evolution of the relative momentum $< K_R >$ as a function of the reaction time. The reaction under consideration is ^{40}Ca -^{40}Ca using the hard EOS. The upper part of the figure is calculated for the impact parameter 2 fm and the bombarding energies 50 MeV/nucl., 125 MeV/nucl., 250 MeV/nucl., 375 MeV/nucl. and 500 MeV/nucl.. The lower part of the figure is for the bombarding energy 500 MeV/nucl. with impact parameters b = 0 fm, 2.5 fm and 5 fm.

Fig.4 Time evolution of the average temperature and matter density as a function of the reaction time. The upper part shows the evolution of the temperature at incident energies 125 MeV/nucl., 250 MeV/nucl., 375 MeV/nucl. and 500 MeV/nucl.. The lower part displays the matter densities at bombarding energies 125 MeV/nucl. and 500 MeV/nucl..

Fig.5 The same as in fig. 4 but at the bombarding energy of 500 MeV/nucl. and at

impact parameters b = 0 fm, 2.5 fm, 5.0 fm and 7.5 fm.

Fig.6 The same as in fig. 5 but at a bombarding energy of 500 MeV/nucl. and at an impact parameter b = 0.25 b_{max}. Here five different systems ^{40}Ca -^{40}Ca, ^{28}Si -^{28}Si, ^{20}Ne -^{20}Ne, ^{16}O -^{16}O and ^{12}C-^{12}C are considered.

Fig.7 The same as in fig.6, but at incident energy of 500 MeV/nucl. The upper and lower parts show the temperature using the hard and the soft EOS's at impact parameters b = 0 fm and 5 fm, respectively.

Fig.8 The maximal value of the temperature as a function of the bombarding energy. Here the hard EOS is used. Note that various colliding systems are considered at an impact parameter b = 0.25 b_{max}. The solid line is the parametrized curve given by eq.(11)

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